

# EXOTIC $\rho^\pm\rho^0$ STATE PHOTOPRODUCTION

N.N. Achasov and G.N. Shestakov

*Laboratory of Theoretical Physics, S.L. Sobolev Institute for Mathematics,  
630090, Novosibirsk 90, Russia*

## Abstract

It is shown that the list of unusual mesons planned for a careful study in photoproduction can be extended by the exotic states  $X^\pm(1600)$  with  $I^G(J^{PC}) = 2^+(2^{++})$  which should be looked for in the  $\rho^\pm\rho^0$  decay channels in the reactions  $\gamma N \rightarrow \rho^\pm\rho^0N$  and  $\gamma N \rightarrow \rho^\pm\rho^0\Delta$ . The full classification of the  $\rho^\pm\rho^0$  states by their quantum numbers is presented. A simple model for the spin structure of the  $\gamma p \rightarrow f_2(1270)p$ ,  $\gamma p \rightarrow a_2^0(1320)p$ , and  $\gamma N \rightarrow X^\pm(N, \Delta)$  reaction amplitudes is formulated and the tentative estimates of the corresponding cross sections at the incident photon energy  $E_\gamma \approx 6$  GeV are obtained:  $\sigma(\gamma p \rightarrow f_2(1270)p) \approx 0.12 \mu\text{b}$ ,  $\sigma(\gamma p \rightarrow a_2^0(1320)p) \approx 0.25 \mu\text{b}$ ,  $\sigma(\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm\rho^0 N) \approx 0.018 \mu\text{b}$ , and  $\sigma(\gamma p \rightarrow X^- \Delta^{++} \rightarrow \rho^- \rho^0 \Delta^{++}) \approx 0.031 \mu\text{b}$ . The problem of the  $X^\pm$  signal extraction from the natural background due to the other  $\pi^\pm\pi^0\pi^+\pi^-$  production channels is discussed. In particular the estimates are presented for the  $\gamma p \rightarrow h_1(1170)\pi^+n$ ,  $\gamma p \rightarrow \rho'^+n \rightarrow \pi^+\pi^0\pi^+\pi^-n$ , and  $\gamma p \rightarrow \omega\rho^0p$  reaction cross sections. Our main conclusion is that the search for the exotic  $X^\pm(2^+(2^{++}))$  states is quite feasible at JEFFLAB facility. The expected yield of the  $\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm\rho^0 N$  events in a 30-day run at the 100% detection efficiency approximates  $2.8 \times 10^6$  events.

PACS number(s): 13.60.Le, 12.40.Nn, 14.40.Ev

email: achasov@math.nsc.ru  
email: shestako@math.nsc.ru

## I. INTRODUCTION

The intensive photon beam with an energy of 6 GeV and the CLAS detector at Jefferson Laboratory (JEFLAB) will allow us to perform, to a high accuracy, measurements of the multi-meson photoproduction processes [1-4]. Hunting for various unusual resonant states will be one of the main directions of forthcoming investigations [1-4]. In particular, similar to the current  $e^+e^-$  experiments [5-7], the rare radiative decays  $\phi \rightarrow f_0(980)\gamma \rightarrow \pi\pi\gamma$  and  $\phi \rightarrow a_0^0(980)\gamma \rightarrow \pi^0\gamma\gamma$ , which are an excellent laboratory for studying the makeup of the  $f_0(980)$  and  $a_0^0(980)$  [8-10], will be looked for in the reaction  $\gamma p \rightarrow \phi p$ . It is also proposed to study some states from the  $J^{PC} = 0^{--}$ , even $^{+-}$ , odd $^{-+}$  exotic series, for example, the  $\hat{\rho}(1600)$  state with  $J^{PC} = 1^{-+}$  in the reactions  $\gamma p \rightarrow (\rho\pi, \eta\pi, \eta'\pi, f_1\pi)N$  [2-4].

In the present work, we show that the list of exotic mesons planned for studying in photoproduction at JEFLAB and other facilities can be extended by the states  $X^\pm(1600)$  with  $J^{PC} = 2^{++}$  being members of an isotopic multiplet with the isospin  $I = 2$ . These states should be looked for in the  $\rho^\pm\rho^0$  decay channels in the reactions  $\gamma p \rightarrow \rho^+\rho^0(n, \Delta^0)$ ,  $\gamma n \rightarrow \rho^-\rho^0(p, \Delta^+)$ ,  $\gamma p \rightarrow \rho^-\rho^0\Delta^{++}$ , and  $\gamma n \rightarrow \rho^+\rho^0\Delta^-$  which can occur via the  $\rho$  Regge pole exchange.

As is known, the neutral isotensor tensor state  $X^0(1600, I^G(J^{PC}) = 2^+(2^{++}))$  [11] has been observed near the threshold in the reactions  $\gamma\gamma \rightarrow \rho^0\rho^0$  [12,13] and  $\gamma\gamma \rightarrow \rho^+\rho^-$  [14,15] (see, for reviews, Refs. [16,17] and the ARGUS data shown in Figure 1, as an illustration of the situation in the  $\gamma\gamma$  collisions). The specific features due to this state in the reactions  $\gamma\gamma \rightarrow \rho\rho$  were predicted in Refs. [18,19] on the basis of the  $q^2\bar{q}^2$  MIT-bag model [20]. While a resonance interpretation of the data on the reactions  $\gamma\gamma \rightarrow \rho\rho$  seems to us to be most adequate, it is not yet completely unquestionable and finally established (see, for example, discussions in Refs. [16,17,21,22]). Similar to the other candidates in “certified” exotic states [23], the state  $X^0(1600, 2^+(2^{++}))$  is in need of further confirmations and it is not improbable that just photoproduction of its charged partners,  $X^\pm$ , will become crucial in this respect <sup>1</sup>.

In Sec. II, we classify the  $\rho^\pm\rho^0$  states by their quantum numbers, indicate those states which can be essential near the nominal  $\rho\rho$  threshold, and briefly discuss the resonances known coupled to the  $\pi^\pm\pi^0\pi^+\pi^-$  channels which can be the sources of the background for the  $X^\pm(2^+(2^{++}))$  signals. In Sec. III, using the available information on the processes  $\gamma\gamma \rightarrow f_2(1270) \rightarrow \pi\pi$ ,  $\gamma\gamma \rightarrow a_2^0(1320) \rightarrow \pi^+\pi^-\pi^0, \pi^0\eta$ , and  $\gamma\gamma \rightarrow \rho\rho$ , the vector dominance model (VDM), and the factorization property of the Regge pole exchanges, we establish the spin structure for the  $\gamma p \rightarrow f_2(1270)p$ ,  $\gamma p \rightarrow a_2^0(1320)p$ , and  $\gamma N \rightarrow X^\pm(N, \Delta)$  reaction amplitudes and estimate the values of the corresponding cross sections. At the incident photon energy  $E_\gamma \approx 6$  GeV, we obtain  $\sigma(\gamma p \rightarrow f_2(1270)p) \approx 0.12 \mu\text{b}$ ,  $\sigma(\gamma p \rightarrow a_2^0(1320)p) \approx 0.25 \mu\text{b}$ ,  $\sigma(\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm\rho^0 N) \approx 0.018 \mu\text{b}$  and  $\sigma(\gamma p \rightarrow X^-\Delta^{++} \rightarrow \rho^-\rho^0\Delta^{++}) = 3\sigma(\gamma p \rightarrow X^+\Delta^0 \rightarrow \rho^+\rho^0\Delta^0) \approx 0.031 \mu\text{b}$ .

In Sec. IV, we discuss, mainly by the example of the reactions  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$ , the problem of the  $X^\pm$  state extraction from the natural background caused by the other  $\pi^\pm\pi^0\pi^+\pi^-$  production channels and estimate a number of relevant partial cross sections.

Using, as a guide, information on the statistics planned for the rare decays of the  $\phi$  meson produced in the reaction  $\gamma p \rightarrow \phi p$  [1,2], we come to the conclusion that the search

---

<sup>1</sup>The cross sections for hadroproduction of the  $X^0(1600, 2^+(2^{++}))$  doubly charged partners were estimated in Ref. [24].

for the exotic  $X^\pm(2^+(2^{++}))$  states near the  $\rho\rho$  threshold at JEFLAB facility should be expected quite successful. New knowledge about hadron spectroscopy, which will be obtained as a result of such measurements, seem to be extremely important.

## II. STATES OF THE $\rho^\pm\rho^0$ SYSTEM

These states have the positive  $G$  parity. Their classification by the total isospin  $I$ , total moment  $J$ ,  $P$  parity,  $C$  parity of a neutral component of the isotopic multiplet, total spin  $S$ , and total orbital angular moment  $L$  is presented in Table I. As seen from the table, five of eight series of the  $\rho^\pm\rho^0$  states are exotic, i.e. forbidden in the  $q\bar{q}$  system <sup>2</sup>. The specific examples of the resonance states exist so far only in the first, second, and eight series <sup>3</sup>. Among the states with even  $J$ , only the exotic ones with  $I^G(J^{PC}) = 2^+(0^{++})$  and  $2^+(2^{++})$  possess the  ${}^{2S+1}L_J$  configurations with  $L = 0$  and therefore can, in principle, effectively manifest themselves near the nominal  $\rho\rho$  threshold ( $2m_\rho \approx 1540$  MeV). Note that one can speak with confidence about coupling to the  $\rho\rho$  channel only in the case of the  $\rho_3(1690)$  and  $X(1600, 2^+(2^{++}))$  states. Indeed, in the dominant  $\rho_3(1690) \rightarrow 4\pi$  decay, the  $\rho\rho$  mode may reach of 50% [26], and the  $X^0(1600, 2^+(2^{++}))$  state has been discovered for the first time just in the  $\rho\rho$  channel (see the Introduction). The  $b_1(1235)$  resonance lies deeply under the  $\rho\rho$  threshold and has been observed the in the four-pion channel only in the  $\omega\pi$  mode [26]. As for the  $\rho(1700) \rightarrow 4\pi$  decay then the available data do not contradict to the absent of the  $\rho\rho$  component in this decay [26] <sup>4</sup>. However, for any  $4\pi$  decay mechanisms the  $\rho(1700)$  and  $\rho_3(1690)$  resonance contributions to the reactions  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^- (N, \Delta)$  should be considered as a possible important and, may be, major background for signals from the  $X^\pm(1600, 2^+(2^{++}))$  production. Note that the  $\rho^\pm(1700)$  and  $\rho_3^\pm(1690)$  states have not yet been observed in photoproduction and that the available results on diffractive  $\rho^0(1700)$  and  $\rho_3^0(1690)$  photoproduction for  $E_\gamma < 10$  GeV are in need of refinements.

---

<sup>2</sup> Notice that we do not include in Table I two exotic  $\rho^\pm\rho^0$  states with  $I^G(J^{PC}) = 1^+(0^{--})$  and  $1^+(0^{+-})$  because they correspond to the  ${}^{2S+1}L_J = {}^3P_0$ , and  ${}^1S_0$ ,  ${}^5D_0$  configurations that are forbidden by Bose symmetry in the limit of the stable  $\rho$  mesons. Therefore, in the realistic case, the production amplitudes of two unstable  $\rho$  mesons with the four-momenta  $q_1$  and  $q_2$  have to be proportional, for these states, to the factor  $(q_1^2 - q_2^2)$  which forbids a “simultaneous” appearance of two  $\rho$  peaks in the  $P$ -wave mass spectra of the final  $(\pi\pi)_1$  and  $(\pi\pi)_2$  systems. For the same reason, we omit some  ${}^{2S+1}L_J$  configurations in the right column of Table I, for example, the  ${}^3S_1$  configuration for the  $I^G(J^{PC}) = 2^+(1^{++})$  state and  ${}^3D_2$  for  $2^+(2^{++})$ .

<sup>3</sup>The  $\rho_2$  state from the third series with  $I^G(J^{PC}) = 1^+(2^{--})$  and with the expected mass near 1700 MeV [25] and also its isoscalar partners  $\omega_2$  and  $\phi_2$  have not yet been observed in multibody mass spectra [26]. However, the current data on the reaction  $\pi^- p \rightarrow a_0^0(980)n$  are conclusively indicative of the  $\rho_2$  Regge pole exchange [27]. Besides the  $a_0\pi$  and  $\rho\rho$  channels, the  $\rho_2$  state may be also coupled to  $\omega\pi$ ,  $a_2\pi$ ,  $a_1\pi$ ,  $h_1\pi$ ,  $b_1\eta$ ,  $\rho(\pi\pi)_S$ -wave, and  $\rho f_2$  systems.

<sup>4</sup>In this context the notation  $\rho(1700)$  [26] is used somewhat conditionally. Actually, by the  $\rho(1700)$  we mean the whole  $4\pi$  enhancement with  $I^G(J^{PC}) = 1^+(1^{--})$  which has been observed in the reactions  $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$  and  $\gamma p \rightarrow \pi^+\pi^-\pi^0\pi^0p$  (however, perhaps with the  $\rho_3(1690)$  admixture [28]), i.e. the “old”  $\rho'$  (or  $\rho(1600)$ ) resonance [29]. Taking into account the splitting of the  $\rho'$  into two  $\rho$ -like resonances ( $\rho(1450)$  and  $\rho(1700)$  [30]) in photoproduction, according to the available data [26,31-36], is not critical at least for our purposes.

### III. ESTIMATES OF THE $f_2(1270)$ , $a_2^0(1320)$ , AND $X^\pm(1600, 2^+(2^{++}))$ PHOTOPRODUCTION CROSS SECTIONS

We shall assume that the  $\gamma p \rightarrow f_2 p$ ,  $\gamma p \rightarrow a_2^0 p$  and  $\gamma N \rightarrow X^\pm(N, \Delta)$  reaction cross sections at high energies are dominated by the Regge pole exchanges with natural parity, i.e. by the  $\rho^0$ ,  $\omega$ , and  $\rho^\pm$  Regge poles<sup>5</sup>. Note that the one-pion exchange is forbidden in these reactions and we neglect by the  $b_1$ ,  $h_1$ ,  $\rho_2$ , and  $\omega_2$  exchanges with unnatural parity. In order to establish the spin structure for the  $\gamma p \rightarrow f_2 p$ ,  $\gamma p \rightarrow a_2^0 p$ , and  $\gamma N \rightarrow X^\pm(N, \Delta)$  reaction amplitudes in the Regge region and estimate the corresponding cross sections we shall first discuss the  $f_2$ ,  $a_2^0$ , and  $X^0$  production in  $\gamma\gamma$  collisions (our approach is closely related essentially with that of Stodolsky and Sakurai [37] to the construction of the  $\rho$  meson exchange model for  $\Delta^{++}$  production in the reaction  $\pi^- p \rightarrow \pi^0 \Delta^{++}$ ).

As is known, in the c.m. system in the reactions  $\gamma\gamma \rightarrow f_2 \rightarrow \pi\pi$  [38],  $\gamma\gamma \rightarrow a_2^0 \rightarrow (\pi^+ \pi^- \pi^0, \pi^0 \eta)$  [39,40] and  $\gamma\gamma \rightarrow \rho\rho$  near the threshold [13,15] (see Fig. 1), formation of the tensor ( $J^P = 2^+$ ) resonances occur mainly in the  $J_z = \pm 2$  spin states with the spin quantization  $z$ -axis taken along the momentum one of two photons; in so doing  $J_z = \lambda_1 - \lambda_2$ , where  $\lambda_1$  and  $\lambda_2$  are the photon helicities. Two-photon excitation of the  $2^+$  resonances in the pure  $J_z = \pm 2$  states corresponds to the production amplitude of the form  $g_{2+\gamma\gamma} T_{\mu\nu}^{\lambda*} F_{\mu\tau}^{\gamma_1} F_{\nu\tau}^{\gamma_2}$  [18,41,42], where  $T_{\mu\nu}^{\lambda*}$  is the symmetric traceless polarization tensor for the final  $2^+$  resonance with helicity  $\lambda$ ,  $F_{\mu\nu}^{\gamma_i} = k_{i\mu} \epsilon_\nu^{\lambda_i}(k_i) - k_{i\nu} \epsilon_\mu^{\lambda_i}(k_i)$ , and  $\epsilon_\mu^{\lambda_i}(k_i)$  is the usual polarization vector for the photon with the four-momentum  $k_i$  and helicity  $\lambda_i = \pm 1$  ( $i = 1, 2$ ). Indeed, in the  $\gamma\gamma$  c.m. system, the spatial part of the tensor  $I_{\mu\nu} = (F_{\mu\tau}^{\gamma_1} F_{\nu\tau}^{\gamma_2} + F_{\mu\tau}^{\gamma_2} F_{\nu\tau}^{\gamma_1})/2$  for  $\lambda_1 = \lambda_2$  has the form  $|\vec{k}_1|^2 [\epsilon_l^1(k_1) \epsilon_m^1(k_2) + \epsilon_l^{-1}(k_1) \epsilon_m^{-1}(k_2) + \epsilon_l^0(k_1) \epsilon_m^0(k_2)]$  (where  $\vec{\epsilon}^0(k_i) = \vec{k}_i / |\vec{k}_i|$  and  $l, m = 1, 2, 3$ ) and corresponds to the wave function of the  $\gamma\gamma$  system with  $J = 0$  which is orthogonal to  $T_{lm}^{\lambda*}$  with  $\lambda = J_z = 0$ , whereas, for  $\lambda_1 = -\lambda_2 = \pm 1$ ,  $I_{lm} = 2|\vec{k}_1|^2 \epsilon_l^{\pm 1}(k_1) \epsilon_m^{\mp 1}(k_2)$  corresponds to the states of the  $\gamma\gamma$  system with the total moment  $J = 2$  and  $J_z = \pm 2$ .

In the spirit of the vector meson dominance (VDM) and naive quark model, we shall consider that the  $\gamma V \rightarrow 2^+$  transition amplitudes have the form  $g_{2+\gamma V} T_{\mu\nu}^{\lambda*} F_{\mu\tau}^V F_{\nu\tau}^V$  (where  $V = \rho, \omega$ ,  $F_{\nu\tau}^V = k_{V\nu} \epsilon_\tau^{\lambda_V}(k_V) - k_{V\tau} \epsilon_\nu^{\lambda_V}(k_V)$ , and  $\epsilon^{\lambda_V}\tau(k_V)$  is the polarization vector of the  $V$  meson with the four-momentum  $k_V$  and helicity  $\lambda_V$ ) and that the coupling constants  $g_{2+\gamma V}$  and  $g_{2+\gamma\gamma}$  obey the following relations:

$$g_{f_2\gamma\rho} = 3g_{f_2\gamma\omega} = g_{a_2\gamma\omega} = 3g_{a_2\gamma\rho} = \frac{9}{10}g_{f_2\gamma\gamma} \left( \frac{f_\rho}{e} \right) = \frac{1}{2}g_{a_2\gamma\gamma} \left( \frac{f_\omega}{e} \right) = \frac{1}{2}g_{a_2\gamma\gamma} \left( \frac{3f_\rho}{e} \right). \quad (1)$$

Small deviations known from these relations are not of principle for the following estimates. Using Eq. (1) and the conventional values for the widths [26]

$$\Gamma_{f_2\gamma\gamma} = \frac{g_{f_2\gamma\gamma}^2}{4\pi} \frac{m_{f_2}^3}{80} \approx 2.45 \text{ keV} \quad \text{and} \quad \Gamma_{\rho^0 e^+ e^-} \approx \frac{\alpha^2}{3} \frac{m_\rho}{(f_\rho^2/4\pi)} = 6.77 \text{ keV}, \quad (2)$$

where  $\alpha = e^2/4\pi = 1/137$ , we find that  $f_\rho^2/4\pi \approx 2.02$ ,

$$\frac{g_{f_2\gamma\rho}^2}{4\pi} \approx 0.0212 \text{ GeV}^{-2}, \quad \text{and} \quad \Gamma_{f_2\gamma\rho} = \frac{g_{f_2\gamma\rho}^2}{4\pi} \frac{|\vec{k}_\gamma|^3}{5} \left[ 1 + \frac{1}{2}r + \frac{1}{6}r^2 \right] \approx 340 \text{ keV}, \quad (3)$$

---

<sup>5</sup>Wherever possible, we do not indicate, for short, the resonance masses, i.e., we write, for example,  $f_2$  instead of  $f_2(1270)$ , etc.

where  $r = m_\rho^2/m_{f_2}^2$  and  $|\vec{k}_\gamma| = m_{f_2}(1-r)/2$ .

Let us now construct the  $s$ -channel helicity amplitudes  $M_{\lambda_{f_2}\lambda_p'\lambda_\gamma\lambda_p}^{(\rho)}$  for the reaction  $\gamma p \rightarrow f_2 p$  corresponding to the elementary  $\rho$  exchange. As is well known, at high energies and fixed momentum transfers, such amplitudes possess one of the major properties of the Regge pole amplitudes, namely, the factorization property of the spin structures for mesonic and baryonic vertices. Thus, in the c.m. system,

$$M_{\lambda_{f_2}\lambda_p'\lambda_\gamma\lambda_p}^{(\rho)} = V_{\lambda_{f_2}\lambda_\gamma}^{(\rho)}(t) \left( \frac{-2s}{t - m_\rho^2} \right) V_{\lambda_p'\lambda_p}^{(\rho)}(t), \quad (4)$$

where  $s = (k+p)^2$ ,  $t = (q-k)^2$ ,  $k+p = q+p'$ ,  $k, q, p, p'$  and  $\lambda_\gamma, \lambda_{f_2}, \lambda_p, \lambda_p'$  are the four-momenta and helicities of the photon,  $f_2$  meson, initial and final protons respectively. According to the model suggested above for the  $\gamma\rho f_2$  interaction, the corresponding vertex function looks as follows:

$$\begin{aligned} V_{\lambda_{f_2}\lambda_\gamma}^{(\rho)}(t) &= -(g_{f_2\gamma\rho}/2) \xi_{jl}^{\lambda_{f_2}*} \times \\ &\times \left[ \epsilon_j^{\lambda_\gamma} \Delta_l + \frac{(\vec{\epsilon}^{\lambda_\gamma} \vec{\Delta})}{m_{f_2}} n_{0j} \Delta_l + \frac{(\vec{\epsilon}^{\lambda_\gamma} \vec{n})}{m_{f_2}} n_j n_{0l} + \frac{1}{2} (\vec{\epsilon}^{\lambda_\gamma} \vec{\Delta}) n_{0j} n_{0l} \left( 1 - \frac{t}{m_{f_2}^2} \right) \right], \end{aligned} \quad (5)$$

where  $\xi_{jl}^{\lambda_{f_2}*}$  is the three-dimensional tensor spin wave function of the final  $f_2$  meson in its rest frame ( $j, l = 1, 2, 3$ ),  $\vec{\Delta} = \vec{q} - \vec{k}$ ,  $t \approx -\vec{\Delta}^2$ ,  $\vec{\epsilon}^{\lambda_\gamma}$  is the three-dimensional polarization vector of the photon, the vector  $\vec{n}_0 = \vec{k}/|\vec{k}|$  is aligned along the  $z$  (or 3) axis, and the vector  $\vec{n} = [\vec{n}_0 \vec{\Delta}]$  is aligned along the  $y$  (or 2) axis which is the normal to the reaction plane. Note that the explicit form of the vertex function  $V_{\lambda_p'\lambda_p}^{(\rho)}(t)$  will not be required in the following; here we also neglect  $t_{\min} \approx -m_p^2 m_{f_2}^4/s^2$ . Eq. (5) yields

$$V_{\pm 2 \pm 1}^{(\rho)}(t) = \pm \frac{g_{f_2\gamma\rho} \sqrt{-t}}{2\sqrt{2}}, \quad V_{\pm 1 \pm 1}^{(\rho)}(t) = \frac{g_{f_2\gamma\rho} t}{2\sqrt{2} m_{f_2}}, \quad V_{0 \pm 1}^{(\rho)}(t) = \mp \frac{g_{f_2\gamma\rho} t \sqrt{-t}}{4\sqrt{3} m_{f_2}^2}. \quad (6)$$

Moreover, in our model, the relative contributions of the helicity amplitudes with  $\lambda_{f_2} - \lambda_\gamma = \pm 3$  and  $\pm 2$  vanish asymptotically. Eq. (6) implies that, for  $-t < 1 \text{ GeV}^2$ , the contributions to the differential cross sections from the amplitudes with  $\lambda_{f_2} = \pm 1$  and  $\lambda_{f_2} = 0$  are suppressed relative to those of the amplitudes with  $\lambda_{f_2} = \pm 2$  by the factors  $-t/m_{f_2}^2$  and  $t^2/6m_{f_2}^4$  respectively. Thus, our model predicts a dominance of the  $f_2$  production amplitudes with  $\lambda_{f_2} = \pm 2$  in the region  $-t < 1 \text{ GeV}^2$ . Going to the real physical amplitudes caused by the  $\rho$  Regge pole exchange,  $\widehat{M}_{\lambda_{f_2}\lambda_p'\lambda_\gamma\lambda_p}^{(\rho)}$ , we shall accept this prediction as a natural assumption and take into account hereinafter just the amplitudes  $\widehat{M}_{\pm 2\lambda_p'\pm 1\lambda_p}^{(\rho)}$ . Denote the Regge vertex functions (Regge residues), which appear in  $\widehat{M}_{\lambda_{f_2}\lambda_p'\lambda_\gamma\lambda_p}^{(\rho)}$ , by  $\widehat{V}_{\lambda_{f_2}\lambda_\gamma}^{(\rho)}(t)$  and  $\widehat{V}_{\lambda_p'\lambda_p}^{(\rho)}(t)$ . The parity conservation and residue factorization [43] yield  $\widehat{M}_{2\lambda_p'1\lambda_p}^{(\rho)} = -\widehat{M}_{-2\lambda_p'-1\lambda_p}^{(\rho)} = (-1)^{\lambda_p' - \lambda_p} \widehat{M}_{2-\lambda_p'1-\lambda_p}^{(\rho)}$ . Therefore we deal only with two independent amplitudes, for example,  $\widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)}$  and  $\widehat{M}_{2\frac{1}{2}1-\frac{1}{2}}^{(\rho)}$ . Note that the  $\omega$  exchange in the reaction  $\gamma p \rightarrow f_2 p$  quadruples the  $\widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)}$  contribution to the cross section. Indeed, assuming, as in the naive quark model, that  $\widehat{V}_{\lambda_{f_2}\lambda_\gamma}^{(\omega)}(t) = \widehat{V}_{\lambda_{f_2}\lambda_\gamma}^{(\rho)}(t)/3$  (see also Eq. (1)) and  $\widehat{V}_{\lambda_p'=\frac{1}{2}, \lambda_p=\frac{1}{2}}^{(\omega)}(t) = 3\widehat{V}_{\lambda_p'=\frac{1}{2}, \lambda_p=\frac{1}{2}}^{(\rho)}(t)$ , and also degeneracy of the  $\rho$  and  $\omega$  Regge trajectories,

$\alpha_\omega(t) = \alpha_\rho(t)$ , we obtain  $\widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\omega)} = \widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)}$ . On the other hand, the  $\omega$  exchange amplitude with a helicity flip in the nucleon vertex is assumed negligible because  $\widehat{V}_{\frac{1}{2}-\frac{1}{2}}^{(\omega)}(t) \ll \widehat{V}_{\frac{1}{2}-\frac{1}{2}}^{(\rho)}(t)$  and in addition  $\widehat{V}_{\frac{1}{2}-\frac{1}{2}}^{(\omega)}(t)/\sqrt{-t/1\text{GeV}^2} \ll \widehat{V}_{\frac{1}{2}\frac{1}{2}}^{(\omega)}(t)$  (see, for example [44-47]). Finally, for the reaction  $\gamma p \rightarrow f_2 p$  in the standard normalization we have

$$\sigma(\gamma p \rightarrow f_2 p) = \frac{1}{16\pi s^2} \int \left[ 4 \left| \widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)} \right|^2 + \left| \widehat{M}_{2\frac{1}{2}1-\frac{1}{2}}^{(\rho)} \right|^2 \right] dt = 4 \sigma_{nf}^{(\rho)} \left( 1 + \frac{1}{4} R \right), \quad (7)$$

where the integral is taken over the region  $0 < -t < 1 \text{ GeV}^2$  which gives the main contribution to the cross section,  $\sigma_{nf}^{(\rho)}$  denotes the cross section caused by the  $\rho$  exchange amplitude  $\widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)}$  without the nucleon helicity flip, and  $R = \sigma_f^{(\rho)}/\sigma_{nf}^{(\rho)}$  is the ratio of the cross section  $\sigma_f^{(\rho)}$  caused by the amplitude  $\widehat{M}_{2\frac{1}{2}1-\frac{1}{2}}^{(\rho)}$  with the nucleon helicity flip to  $\sigma_{nf}^{(\rho)}$ . To estimate  $R$  we use the data on the  $\pi^- p \rightarrow \pi^0 n$  reaction differential cross section which are described remarkably well in terms of the  $\rho$  Regge pole exchange [48]. Assuming the approximate equality of the slopes  $\Lambda$  for the Regge amplitudes in question<sup>6</sup>, together with factorization of the Regge pole residues, and using the results of Ref. [48], we put

$$R \approx \sigma_f^{(\rho)}(\pi^- p \rightarrow \pi^0 n)/\sigma_{nf}^{(\rho)}(\pi^- p \rightarrow \pi^0 n) \approx 1.5. \quad (8)$$

Note that this estimate for  $R$  can be considered as a lower bound. The point is that  $R$  is proportional to  $1/2\Lambda$  and for the  $\pi^- p$  charge exchange at 6 GeV [48]  $2\Lambda \approx 9 \text{ GeV}^{-2}$  which, generally speaking, is larger than for many other similar reactions.

Let us now obtain a representation similar to Eq. (7) for the cross section of the reaction  $\gamma p \rightarrow a_2^0 p$ . According to the naive quark counting rules, any  $\rho$  exchange amplitude for  $\gamma p \rightarrow a_2^0 p$  is three times smaller than the corresponding one for  $\gamma p \rightarrow f_2 p$  and the  $\omega$  exchange amplitude without the proton helicity flip for  $\gamma p \rightarrow a_2^0 p$  is three times larger than that for  $\gamma p \rightarrow f_2 p$  (see also Eq. (1)); i.e., the reaction  $\gamma p \rightarrow a_2^0 p$  is dominated by the  $\omega$  exchange. Thus, in terms of the  $\rho$  exchange amplitudes pertaining to the reaction  $\gamma p \rightarrow f_2 p$ , for which  $\widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\omega)} = \widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)}$  (see also Eqs. (7),(8)), the cross section for  $\gamma p \rightarrow a_2^0 p$  is given by

$$\begin{aligned} \sigma(\gamma p \rightarrow a_2^0 p) &= \frac{1}{16\pi s^2} \int \left[ \frac{100}{9} \left| \widehat{M}_{2\frac{1}{2}1\frac{1}{2}}^{(\rho)} \right|^2 + \frac{1}{9} \left| \widehat{M}_{2\frac{1}{2}1-\frac{1}{2}}^{(\rho)} \right|^2 \right] dt = \\ &= \frac{100}{9} \sigma_{nf}^{(\rho)} \left( 1 + \frac{1}{100} R \right) \approx \frac{100}{9} \sigma_{nf}^{(\rho)}. \end{aligned} \quad (9)$$

Further, let us notice that exactly the same relation between the  $\omega$  and  $\rho$  exchanges, as in  $\gamma p \rightarrow a_2^0 p$ , takes place in the reaction  $\gamma p \rightarrow \pi^0 p$  the cross section of which is dominated by the same exchanges [45-47,49-51]. Furthermore, the helicity change in the mesonic Regge vertices is equal to 1 both in  $\gamma p \rightarrow \pi^0 p$  and in our model for the reaction  $\gamma p \rightarrow a_2^0 p$  (and  $\gamma p \rightarrow f_2 p$ ), so that the all corresponding residues are proportional to  $\sqrt{-t}$ . Defining the  $\omega \rightarrow \pi^0 \gamma$  decay amplitude in the conventional form  $g_{\omega\gamma\pi} \varepsilon_{\mu\nu\tau\kappa} \epsilon_\mu^{\lambda\omega}(k_\omega) k_{\omega\nu} \epsilon_\tau^{\lambda\gamma}(k_\gamma) k_{\gamma\kappa}$ , we find in the case of the elementary  $\omega$  and  $\rho$  exchanges that without any numerical factors

---

<sup>6</sup>Here we have in mind the usual exponential parametrization, according to which any Regge amplitude is taken to be proportional to  $e^{\Lambda t}$ , where the slope  $\Lambda = \Lambda^0 + \alpha' \ln(s/s_0)$ ,  $\alpha'$  is that of the Regge pole trajectory,  $s_0 = 1 \text{ GeV}^2$ , and  $\Lambda^0$  is determined by fitting to the data.

$\sigma(\gamma p \rightarrow a_2^0 p) / \sigma(\gamma p \rightarrow \pi^0 p) = g_{a_2\gamma\omega}^2 / g_{\omega\gamma\pi}^2$ . Thus, it is reasonable to suppose that, in the realistic case of the Reggeized  $\omega$  and  $\rho$  exchanges, such a ratio can be estimated as follows:

$$\frac{\sigma(\gamma p \rightarrow a_2^0 p)}{\sigma(\gamma p \rightarrow \pi^0 p)} \approx \frac{g_{a_2\gamma\omega}^2}{g_{\omega\gamma\pi}^2} \frac{\Lambda_\pi^2}{\Lambda_{a_2}^2}, \quad (10)$$

where  $\Lambda_\pi$  and  $\Lambda_{a_2}$  are the Regge slopes for the  $\pi^0$  and  $a_2^0$  photoproduction amplitudes respectively. To get a feeling for the influence of the slopes in the absence of any information about  $\Lambda_{a_2}$ , we make the *ad hoc* assumption that  $\Lambda_{a_2} \approx \Lambda_\pi / 1.225$ , or  $\Lambda_\pi^2 / \Lambda_{a_2}^2 \approx 1.5$ . According to Refs. [49-51],  $\sigma(\gamma p \rightarrow \pi^0 p) \approx 0.32 \mu\text{b}$  at  $E_\gamma \approx 6 \text{ GeV}$ . From the relations  $\Gamma_{\omega\gamma\pi} = (g_{\omega\gamma\pi}^2 / 4\pi) |\vec{k}_\gamma|^3 / 3 \approx 715 \text{ keV}$  [26] and Eqs. (1), (3) we get  $g_{\omega\gamma\pi}^2 / 4\pi \approx 0.0394 \text{ GeV}^{-2}$  and  $g_{a_2\gamma\omega}^2 / g_{\omega\gamma\pi}^2 \approx 0.538$  which need be substitute in Eq. (10). Putting all this together, we find from Eqs. (7) – (10) that at  $E_\gamma \approx 6 \text{ GeV}$  we can expect

$$\sigma(\gamma p \rightarrow f_2 p) \approx 0.12 \mu\text{b} \quad \text{and} \quad \sigma(\gamma p \rightarrow a_2^0 p) \approx 0.25 \mu\text{b}. \quad (11)$$

Unfortunately, the data on the reactions  $\gamma p \rightarrow f_2 p$  and  $\gamma p \rightarrow a_2^0 p$  are very poor. From the experiments as carried out at comparable energies in the late 60s it is known only that  $\sigma(\gamma p \rightarrow f_2 p \rightarrow \pi\pi p) = 0.06 \pm 0.30 \mu\text{b}$  for  $4.5 < E_\gamma < 5.8 \text{ GeV}$  [52],  $\sigma(\gamma p \rightarrow a_2^0 p) < 0.35 \mu\text{b}$  for  $2.2 < E_\gamma < 5.8 \text{ GeV}$  [52],  $\sigma(\gamma p \rightarrow f_2 p \rightarrow \pi\pi p) < 0.5 \mu\text{b}$  and  $\sigma(\gamma p \rightarrow a_2^0 p \rightarrow \pi^+ \pi^- \pi^0 p) < 0.4 \mu\text{b}$  at  $5.25 \text{ GeV}$  [53], and also  $\sigma(\gamma p \rightarrow f_2 p \rightarrow \pi^+ \pi^- p) \leq 0.7 \pm 0.4 \mu\text{b}$  at  $4.3 \text{ GeV}$  [54]. At higher energies, the reactions  $\gamma p \rightarrow \pi^+ \pi^- p$  and  $\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$  are dominated by two- and three-pion states producing mainly via the Pomeron exchange. Such states have been investigated in some detail. However, the reached accuracy do not yet allow certain conclusions to be made concerning the presence of the  $C$ -odd Regge exchanges. Let us consider as an example the data on the reaction  $\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$  in the energy range  $20 - 70 \text{ GeV}$  obtained by the Omega Photon Collaboration [53]. Assuming the  $1/E_\gamma$  energy dependence for  $\sigma(\gamma p \rightarrow a_2^0 p)$ , which certainly gives an upper limit of the cross section as  $E_\gamma$  increases, and thus extrapolating the value for  $\sigma(\gamma p \rightarrow a_2^0 p)$  from Eq. (11) to the region  $20 < E_\gamma < 70 \text{ GeV}$ , we obtain the averaged  $a_2^0$  production cross section times branching ratio of  $a_2$  to  $\rho\pi$  of about 24 nb. Note that the observed three-pion production cross section in the three-pion mass range from 1.2 to 1.5 GeV is nearly 600 nb [53]. Furthermore, one can see that the height of the  $a_2^0$  peak above a large and smooth background in the three-pion mass spectrum is about a factor of 2.5 smaller than that of the observed “ $\omega'(1670)$ ” peak, because for the latter  $\sigma \times B \approx 100 \text{ nb}$  and the peak width  $\approx 160 \text{ MeV}$  [53]. Such a maximum possible enhancement of the three-pion mass spectrum in the  $a_2^0(1320)$  region turns out to be somewhat less in magnitude than the existing (8 – 9)% double statistical errors. Thus, it is clear that more efforts are needed to provide a reliable observation of the reactions  $\gamma p \rightarrow f_2 p$  and  $\gamma p \rightarrow a_2^0 p$ . In this connection we would like especially to note the reactions  $\gamma p \rightarrow \pi^0 \pi^0 p$  and  $\gamma p \rightarrow \pi^0 \eta p$  with the peripherally produced  $\pi^0 \pi^0$  and  $\pi^0 \eta$  pairs, which can only proceed via  $C$ -odd exchanges and therefore have to be dominated by the production of the  $f_0(980)$ ,  $f_2(1270)$  and  $a_0^0(980)$ ,  $a_2^0(1320)$  resonances with small background.

Exactly the same approach to the reactions  $\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm \rho^0 N$  leads to the estimate

$$\begin{aligned} \sigma(\gamma p \rightarrow X^+ n \rightarrow \rho^+ \rho^0 n) &= \sigma(\gamma n \rightarrow X^- p \rightarrow \rho^- \rho^0 p) \approx \\ &\approx \frac{9}{50} \sigma(\gamma p \rightarrow a_2^0 p) (1 + R) \frac{g_{X^\pm \gamma \rho^\pm}^2 B(X^\pm \rightarrow \rho^\pm \rho^0)}{g_{f_2 \gamma \rho}^2} \approx 0.018 \mu\text{b}. \end{aligned} \quad (12)$$

Here we have used Eqs. (3), (8), (11) and, to avoid the addition model dependent assumptions, estimated the value of  $(g_{X^\pm\gamma\rho^\pm}^2/4\pi) B(X^\pm \rightarrow \rho^\pm\rho^0)$  using the data on  $\sigma(\gamma\gamma \rightarrow \rho^0\rho^0)$  [13] shown in Fig. 1 and the following transparent relations:

$$\begin{aligned} \frac{g_{X^\pm\gamma\rho^\pm}^2}{4\pi} B(X^\pm \rightarrow \rho^\pm\rho^0) &= \frac{9}{8} \frac{g_{X^0\gamma\rho^0}^2}{4\pi} B(X^0 \rightarrow \rho^0\rho^0) = \frac{9}{8} \left( \frac{f_\rho}{e} \right)^2 \frac{g_{X^0\gamma\gamma}^2}{4\pi} B(X^0 \rightarrow \rho^0\rho^0) \\ &\approx \frac{9}{8} \left( \frac{f_\rho}{e} \right)^2 \frac{4}{\pi^2 \bar{m}} \left( \frac{1}{2} \int_{1.2 \text{ GeV}}^{2.2 \text{ GeV}} \sigma(\gamma\gamma \rightarrow \rho^0\rho^0) dW_{\gamma\gamma} \right) \approx 0.00336 \text{ GeV}^{-2}, \end{aligned} \quad (13)$$

where  $\bar{m} \approx 1.6$  GeV is the average mass of the enhancement observed in  $\gamma\gamma \rightarrow \rho^0\rho^0$ , the integral of the cross section  $\approx 33.2$  nb/GeV, and we have put, on the experience of the previous analyses [17,18], that approximately one half of this value is due to the  $X^0$  resonance contribution.

For the reactions  $\gamma N \rightarrow X^\pm\Delta \rightarrow \rho^\pm\rho^0\Delta$  we also expect

$$\begin{aligned} \sigma(\gamma p \rightarrow X^-\Delta^{++} \rightarrow \rho^-\rho^0\Delta^{++}) &= \sigma(\gamma n \rightarrow X^+\Delta^- \rightarrow \rho^+\rho^0\Delta^-) = \\ &= 3\sigma(\gamma p \rightarrow X^+\Delta^0 \rightarrow \rho^+\rho^0\Delta^0) = 3\sigma(\gamma n \rightarrow X^-\Delta^+ \rightarrow \rho^-\rho^0\Delta^+) \approx 0.031 \mu\text{b}. \end{aligned} \quad (14)$$

This estimate has been obtained simply by multiplying of that from Eq. (12) by the coefficient 1.75. Here we proceed from the fact that in the energy region around 6 GeV the cross section for  $\pi^+p \rightarrow \pi^0\Delta^{++}$ , which is dominated by the  $\rho$  Regge pole exchange [55,56], is approximately 1.5 – 2 times than that for the reaction  $\pi^-p \rightarrow \pi^0n$  with just the same mechanism [48,56]. Note that approximately the same ratio takes place for the  $\gamma p \rightarrow \rho^-\Delta^{++}$  and  $\gamma N \rightarrow \rho^\pm N$  reaction cross sections (less the small one-pion exchange contributions) [57,58].

Let us make two short remarks on the above estimates. Firstly, we consider that these estimates are rather conservative. Secondly, of course, there are absorption corrections to the Regge pole models (see, for example, Refs. [45,46]). They lead to some well known modifications of the  $t$  distributions due to the pure Regge pole exchanges. However, it is reasonable that the  $t$  distributions for the reactions having identical Regge pole mechanisms and an identical spin structure for the dominant helicity amplitudes can remain more or less similar in shape even in the presence of the absorption contributions. Therefore, for example, Eq. (10) may well be more general then its derivation within the framework of the Regge pole approximation. In fact, Eq. (10) can be modified only by the difference between the absorption corrections to the  $a_2^0$  and  $\pi^0$  production amplitudes and so a marked change of the estimates for the integrated cross sections seems to be unlikely.

At JELFLAB facility, a 6 GeV photon beam, with intensity  $5 \times 10^7$   $\gamma$ 's/sec, will yield about  $30 \phi$ 's/sec via the photoproduction process  $\gamma p \rightarrow \phi p$ , i.e. there can be accumulated about  $77.8 \times 10^6$   $\gamma p \rightarrow \phi p$  events in a 30-day run [1,2]. The cross section for  $\gamma p \rightarrow \phi p$  is approximately  $0.5 \mu\text{b}$  at  $E_\gamma \approx 6$  GeV [1,2]. Then, according to our estimate (see Eq. (12)), for the reaction  $\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm\rho^0 N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$  one can expect about  $2.8 \times 10^6$  events at the same time. It must be born in mind that such a number of events can be accumulated only at the 100% detection efficiency which is certainly inaccessible in practice. If one assumes that a photon flux of around  $10^7$   $\gamma$ 's/sec and a detection efficiency of around 10% are closer to the reality, then one can expect approximately 56000 useful events. For comparison, full statistics collected by the TASSO, CELLO, TPC/2 $\gamma$ ,

PLUTO, and ARGUS groups for the reaction  $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$  includes 15242 events [17]. At JEFFLAB facility, it is planned to obtain several thousands, tens of thousands, and hundreds of thousands of events for the  $\phi$  meson decays with  $B \approx 10^{-4} - 10^{-2}$  [1,2]. On this scale, the cross section values indicated in Eqs. (12) and (14) are large and the relevant expected significant statistics has not to be wasted. However, there is also a very important and rather complicated question related to the extraction of the exotic  $X^\pm$  signals from a “sea” of all possible  $\pi^\pm\pi^0\pi^+\pi^-$  events. It is this question that we want to discuss in the following.

#### IV. ON THE EXTRACTION OF THE $X^\pm(1600, 2^+(2^{++}))$ SIGNALS

Let us consider the reactions  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$ . In the first place, it is necessary to obtain some general idea about the most important channels of these reactions, in particular, about the values of the corresponding partial cross sections. It is useful to review briefly the results available for the related and more studied reactions  $\gamma N \rightarrow \pi^+\pi^-\pi^+\pi^-N$  in the energy region from 4 to 10 GeV [31-34,52-54,59-69]<sup>7</sup>. So, the values of the  $\gamma N \rightarrow \pi^+\pi^-\pi^+\pi^-N$  cross sections lie in the band from 4 to 7  $\mu\text{b}$  [67,68]. The reaction  $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$  is strongly dominated by  $\rho^0$  and  $\Delta^{++}$  production. There are three the most significant channels in this reaction:  $\gamma p \rightarrow \pi^+\pi^-\pi^-\Delta^{++}$ ,  $\gamma p \rightarrow \rho^0\pi^-\Delta^{++}$  and  $\gamma p \rightarrow \rho^0\pi^+\pi^-p$  [31-33,53,54,60,67] (a similar situation also takes place in  $\gamma n \rightarrow \pi^+\pi^-\pi^+\pi^-n$  [62]). The channels involving  $\Delta^{++}$  production define from 30 to 50% of all  $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$  reaction events. Most of the remainder events are due to  $\rho^0$  production. The  $\gamma p \rightarrow \rho^0\pi^+\pi^-p$  channel is dominated by diffractive  $\rho'^0$  production (see footnote 4). Within the experimental uncertainties, the cross section for  $\gamma p \rightarrow \rho'^0p \rightarrow \rho^0\pi^+\pi^-p$  is energy independent and is roughly 1–2  $\mu\text{b}$  [31-33]. Note that the total number of events collected in all experiments on the reaction  $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$  for  $4 < E_\gamma < 10$  GeV do not exceed  $10^4$ . Specific methods used for separating a large number of particular channels in the reaction  $\gamma p \rightarrow 4\pi p$  have been described in detail in Refs. [31-36,67].

Table II shows the available data on the reactions  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$  for the average incident photon energies from 3.9 to 8.9 GeV. The total cross sections for  $\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$  was measured in four experiments [61-63,68]. In one of them [62], with a total of 151 events, the cross sections for  $\omega$ ,  $\rho^\pm$ ,  $\rho^0$ , and  $\Delta^0$  production were roughly determined (see three left columns in Table II). In addition, the channel cross sections for  $\omega$  production were measured in three more experiments [70-72].

Let us now turn to the phenomenological estimates. For definiteness we shall consider the reaction  $\gamma p \rightarrow \pi^+\pi^0\pi^+\pi^-n$  and its particular channels at  $E_\gamma \approx 6$  GeV (however, the results will also be valid for  $\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$ ). If needed, we shall extrapolate the known cross section values to  $E_\gamma \approx 6$  GeV assuming roughly  $\sigma \sim E_\gamma^{-n}$  with  $n = 2$  and 1 for the one-pion exchange (OPE) mechanism and for the  $\rho$ ,  $a_2$ , and  $\omega$  exchange ones respectively.

We begin with the channel  $\gamma p \rightarrow \omega\Delta^+ \rightarrow \omega\pi^+n$ . Using the data compilations [56,73] and assuming the OPE mechanism dominance, the factorization property of Regge pole residues, and the approximate equality of the slopes for the Regge amplitudes, we get the following estimate

$$\sigma(\gamma p \rightarrow \omega\Delta^+ \rightarrow \omega\pi^+n) \approx$$

---

<sup>7</sup>Here we omit not very essential details concerning the  $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$  and  $\gamma n \rightarrow \pi^+\pi^-\pi^+\pi^-n$  cross section difference (in this connection, see, for example, Refs. [61,63,68]).

$$\approx \sigma^{(OPE)}(\gamma p \rightarrow \omega p) \frac{4}{9} \frac{\sigma(\pi^+ p \rightarrow \rho^0 \Delta^{++})}{\sigma(\pi^- p \rightarrow \rho^0 n)} \approx (0.6 \mu b) \frac{4}{9} 2 \approx 0.53 \mu b, \quad (15)$$

which is in close agreement with that of  $\sigma(\gamma p \rightarrow \omega \Delta^+ \rightarrow \omega \pi^+ n) \approx (0.83 \pm 0.10 \mu b) \times (4.5/6)^2 \approx 0.47 \pm 0.06 \mu b$  found from the data of Ref. [71] presented in Table II. If one suppose that not only  $\omega \Delta^+$  production but the whole channel  $\gamma p \rightarrow \omega \pi^+ n$  can also be dominated by  $\pi$  exchange between the  $\gamma \omega$  and  $p \pi^+ n$  vertices (certainly, in this case, the exchanges with the vacuum quantum numbers are also possible), then, using the data on  $\gamma n \rightarrow \omega \pi^- p$  [62] presented in Table II, one obtains  $\sigma(\gamma p \rightarrow \omega \pi^+ n) \approx (1.4 \pm 0.5 \mu b) \times (4.3/6)^2 \approx 0.72 \pm 0.26 \mu b$ . Owing to the  $\omega$  resonance narrowness, the  $\gamma p \rightarrow \omega \pi^+ n$  channel can be easily separated by cutting a suitable window in the  $\pi^+ \pi^- \pi^0$  invariant mass spectrum.

It is interesting that the cross section for peripheral production of the  $C$ -odd  $\pi^+ \pi^- \pi^0$  system with  $J^P = 1^+$  in  $\gamma p \rightarrow \pi^+ \pi^0 \pi^+ \pi^- n$  can be even larger than that for  $\omega$  production owing to the  $h_1(1170)$  resonance contribution. Because the  $h_1(1170)$  decays mainly into  $\rho \pi$  [26] and its production in  $\gamma p \rightarrow \pi^+ \pi^0 \pi^+ \pi^- n$  can occur via one-pion exchange, we can write

$$\sigma(\gamma p \rightarrow h_1 \pi^+ n) \approx \sigma(\gamma p \rightarrow \omega \pi^+ n) \frac{\Gamma_{h_1 \gamma \pi}}{\Gamma_{\omega \gamma \pi}} \approx [(0.53 - 0.72) \mu b] 2.79 \approx (1.48 - 2) \mu b. \quad (16)$$

Here we have used the above estimates for  $\sigma(\gamma p \rightarrow \omega \pi^+ n)$  and the relation  $\Gamma_{h_1 \gamma \pi} \approx 9 \Gamma_{b_1 \gamma \pi} \approx 9 \times 0.23 \text{ MeV} \approx 2 \text{ MeV}$  [26] which is true for “ideal” octet-singlet mixing in the  $J^{PC} = 1^{+-}$  nonet. There are three intermediate states  $\rho^+ \pi^-$ ,  $\rho^- \pi^+$ , and  $\rho^0 \pi^0$  in the  $h_1 \rightarrow \rho \pi \rightarrow 3\pi$  decay. Each of them, combined with the corresponding kinematical reflections, gives a third of the rate  $h_1 \rightarrow 3\pi$ . Thus,  $\sigma(\gamma p \rightarrow h_1 \pi^+ n \rightarrow \rho^- \pi^+ \pi^+ n) \approx (0.49 - 0.67) \mu b$ , which is roughly compatible with the value of  $\sigma(\gamma n \rightarrow \rho^+ \pi^- \pi^- p) \approx 0.5 \pm 0.5 \mu b$  at 4.3 GeV given in Table II. It is obvious that the channel  $\gamma p \rightarrow X^+ n \rightarrow \rho^+ \rho^0 p$  does not involve  $\rho^-$ -like events. Therefore, a careful examination of the  $\gamma p \rightarrow \rho^- \pi^+ \pi^+ n$  channel will, probably, permit both peripheral  $\rho^- \pi^+$  production and related  $\rho^+ \pi^-$  and  $\rho^0 \pi^0$  events to be successfully selected and excluded. Together with the contribution from the  $h_1(1170)$ , there may also exist the contributions from the  $a_1^0$ ,  $a_2^0$ ,  $\pi_2^0$ , and  $\pi^0(1300)$  resonances in the  $\rho^\mp \pi^\pm$ -like events. However, an analysis shows that the cross sections for peripheral production of these  $C$ -even resonances via  $\rho$  and  $\omega$  exchanges in  $\gamma p \rightarrow \pi^+ \pi^0 \pi^+ \pi^- n$  should be expected to be small. So, as is seen from Eqs. (16) and (15), the  $\rho^\mp \pi^\pm \pi^+ n$ ,  $\rho^0 \pi^0 \pi^+ n$  and  $\omega \pi^+ n$  production channels can contribute to the  $\gamma p \rightarrow \pi^+ \pi^0 \pi^+ \pi^- n$  reaction cross section of about  $2 - 2.5 \mu b$ .

Above we have discussed the peripheral production of the neutral three-pion systems. Now we consider the processes of peripheral production of the  $\pi^+ \pi^- \pi^+$  system, in which the  $a_1^+$ ,  $a_2^+$ ,  $\pi_2^+$  and  $\pi^+(1300)$  resonances can manifest themselves, and, in particular, the reaction  $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \Delta^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^0 n$ . Using the above mentioned data on the reaction  $\gamma p \rightarrow \pi^+ \pi^- \pi^- \Delta^{++}$  for  $E_\gamma < 10$  GeV and assuming the peripheral character of  $\Delta^{++}$  formation, one can obtain the following tentative estimate:

$$\sigma(\gamma p \rightarrow \pi^+ \pi^- \pi^+ \Delta^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^0 n) \approx \frac{2}{9} \sigma(\gamma p \rightarrow \pi^+ \pi^- \pi^- \Delta^{++}) \approx (0.37 - 0.61) \mu b. \quad (17)$$

It is clear that such a type of the  $\pi^+ \pi^- \pi^+ \pi^0 n$  events can be separated, at least, by the specific signs of the  $\Delta^0$  resonance. Formation of  $\Delta^+$  in  $\gamma p$  collisions accompanied by

$\pi^+\pi^-\pi^0$  production we have already discussed (the cross section value for the related process  $\gamma n \rightarrow \pi^+\pi^-\pi^0\Delta^0$  is presented in Table II). The final state  $\pi^+\pi^0\pi^+\Delta^-$  would also require a careful study. If there exists the mode  $\rho^+\pi^+\Delta^-$  in the channel  $\pi^+\pi^0\pi^-\Delta^-$ , then it may be responsible for a possible excess of the yield of the  $\rho^+$  over that of the  $\rho^-$  in  $\gamma p \rightarrow \pi^+\pi^0\pi^+\pi^-n$ . However, the cross section for the  $\gamma p \rightarrow \rho^+\pi^+\Delta^-$  channel is difficult to estimate. A similar statement is, unfortunately, also true both for  $a_2^+\pi^0n$  production with the  $\pi^0n$  system in the  $I = 1/2$  state and for the  $\gamma p \rightarrow \rho^0\pi^+\pi^0n$  channel with the diffractively produced  $\rho^0$  meson.

Let us finally turn to peripheral production of the  $\pi^+\pi^0\pi^+\pi^-$  system. Of course, in this case it is of most interest to estimate the contribution from the  $\rho'^+$  intermediate state (see once again footnote 4). However, we succeeded in doing it only within the framework of the assumptions which reduce to that the ratios  $\sigma(\gamma p \rightarrow \rho'^0p)/\sigma(\gamma p \rightarrow \rho^0p)$  and  $\sigma(\gamma p \rightarrow \rho'^+n)/\sigma(\gamma p \rightarrow \rho^+n)$  are taken to be approximately equal of each other. Let it be the case. We shall also be guided by the following values: at  $E_\gamma \approx 6$  GeV,  $\sigma(\gamma p \rightarrow \rho^0p) \approx 15 \mu\text{b}$  [74],  $\sigma(\gamma N \rightarrow \rho^\pm N) \approx 0.58 \mu\text{b}$  (which is dominated by the  $\rho$  exchange) [57,58], and  $\sigma(\gamma p \rightarrow \rho'^0p \rightarrow \pi^+\pi^-\pi^+\pi^-p) \approx 1.5 \mu\text{b}$  (see the beginning of this section). Hence,  $\sigma(\gamma p \rightarrow \rho'^0p \rightarrow \pi^+\pi^-\pi^+\pi^-p)/\sigma(\gamma p \rightarrow \rho^0p) \approx 1/10$ , and according to our prescription

$$\sigma(\gamma p \rightarrow \rho'^+n \rightarrow \pi^+\pi^0\pi^+\pi^-n) \approx \frac{1}{10} \sigma(\gamma p \rightarrow \rho^+n) \times \left\{ \begin{array}{l} 1 \\ 3/2 \end{array} \right. \approx (0.058 - 0.087) \mu\text{b}, \quad (18)$$

where the factors 1 and 3/2 correspond to the  $\rho' \rightarrow \rho\sigma \rightarrow 4\pi$  ( $\sigma$  denotes the state of the  $S$ -wave  $\pi\pi$  system with  $I = 0$ ) and  $\rho' \rightarrow a_1\pi \rightarrow 4\pi$  decay models respectively. Now we briefly discuss the input assumptions which lead to the relation  $\sigma(\gamma p \rightarrow \rho'^0p)/\sigma(\gamma p \rightarrow \rho^0p) \approx \sigma(\gamma p \rightarrow \rho'^+n)/\sigma(\gamma p \rightarrow \rho^+n)$ . There are two assumptions: 1) diagonal vector dominance for the Regge exchange amplitudes with the vacuum and non-vacuum quantum numbers in the  $t$  channel in the reactions  $\gamma N \rightarrow \rho N$  and  $\gamma N \rightarrow \rho' N$  and 2) universality of the  $\rho$ -Reggeon coupling to hadrons. The diagonal vector dominance assumptions, as applied to the reactions  $\gamma p \rightarrow \rho^0p$  and  $\gamma p \rightarrow \rho'^0p$ , has been discussed, for example, in Refs. [32,34,35,74,75]. In fact, there has been shown in these works that such an approximation, with a glance to the quite natural relations  $\sigma_{tot}(\rho N) \approx \sigma_{tot}(\rho' N) \approx \sigma_{tot}(\pi N)$ , gives a reasonable explanation of the cross section value observed for  $\gamma p \rightarrow \rho'^0p$ . On the other hand, the absence of some evidence for the  $\rho' \rightarrow \rho\rho$  decay permits the diagonal vector dominance model to be also applied to the vertex  $\gamma(\rho^+)\rho'^+$ , where  $(\rho^+)$  is a Reggeon. Adding to this the assumption 2) about  $\rho$ -universality, i.e., about the approximate equality of the  $\rho^0(\rho^+)\rho^+$  and  $\rho'^0(\rho^+)\rho'^+$  vertices, we come to Eq. (18).

It should be noted that the expected suppression of  $\sigma(\gamma p \rightarrow \rho'^+n \rightarrow \pi^+\pi^0\pi^+\pi^-n)$  relative to  $\sigma(\gamma p \rightarrow \rho'^0p \rightarrow \pi^+\pi^-\pi^+\pi^-p)$  is a major reason why we suggest to look for in photoproduction the  $X^\pm$  states rather than the  $X^0$  one.<sup>8</sup>

Comparing Eqs. (12) and (18), we conclude that if one succeeds in selecting the events due to peripheral production of the  $\pi^\pm\pi^0\pi^+\pi^-$  system in  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$ , then the separation of the  $\rho'^\pm$  and  $X^\pm$  contributions would be quite possible with high statistics. In so doing, a detailed simultaneous analysis of all two- and three-pion mass spectra (for

<sup>8</sup> In this connection, we also point out the relation  $\sigma(\gamma N \rightarrow X^0N \rightarrow \rho^0\rho^0N)/\sigma(\gamma N \rightarrow X^\pm N \rightarrow \rho^\pm\rho^0N) = 4/9$  and the possibility of the additional rich background in the  $\rho^0\rho^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$  channel from the  $I = 0$  states.

example,  $\pi^+\pi^0$ ,  $\pi^+\pi^-$ ,  $\pi^+\pi^+$ ,  $\pi^0\pi^-$ ,  $\pi^+\pi^+\pi^0$ ,  $\pi^+\pi^+\pi^-$  and  $\pi^+\pi^-\pi^0$  in  $\gamma p \rightarrow \pi^+\pi^0\pi^+\pi^-n$ ) and corresponding angular distributions has to come into play. Note that the simulation of the mass and angular distributions for the decays  $X \rightarrow \rho\rho \rightarrow 4\pi$  has been described in detail in the literature [12-17]. A detectable reduction of the background from  $\rho'^\pm$  production and, consequently, a much more accurate separation of the  $\rho'^\pm$  and  $X^\pm$  signals can be provided by using polarized photons. As is known, in this case, good analyzers for  $4\pi$  states are the vector  $\vec{Q} = \vec{p}_{\pi_1} + \vec{p}_{\pi_2}$  (where  $\pi_1$  and  $\pi_2$  are equally charged pions) and the photon polarization angle  $\psi$  (for reviews see e.g. [31,73,76,77]). One can make sure that within the simplest production and decay models the  $(\vec{Q}, \psi)$ -distributions for the  $\rho'^\pm$  and  $X^\pm$  states are essentially different. Certainly, because of the great extent, it is more appropriate to carry out the full analysis of the use from polarized photons elsewhere.

As for the  $\rho_3(1690)$  resonance, no analysis has so far been done including its contribution to the description of the observed peaks seen in photoproduction of  $\pi^+\pi^-\pi^+\pi^-$ ,  $\pi^+\pi^0\pi^-\pi^0$  and  $\pi^+\pi^-$  which have been attributed to the  $\rho'$  resonance [28]. However, diffractive production of  $\rho_3^0$  in the  $a_2^\pm\pi^\mp$  decay modes was found in the reaction  $\gamma p \rightarrow \eta\pi^+\pi^-p$  for  $20 < E_\gamma < 70$  GeV [28] and, on the basis of these data, the cross sections  $\sigma(\gamma p \rightarrow \rho_3^0 p \rightarrow \pi^+\pi^-\pi^+\pi^-p) = 0.147 \pm 0.42 \pm 0.32$   $\mu\text{b}$  and  $\sigma(\gamma p \rightarrow \rho_3^0 p \rightarrow \rho^+\rho^-p) = 0.018 \pm 0.016 \pm 0.004$   $\mu\text{b}$  were predicted as well. Furthermore, before the  $\rho'$  state had been discovered, some upper limits for the  $\rho_3^0$  production cross sections were determined, namely,  $\sigma(\gamma p \rightarrow \rho_3^0 p \rightarrow \pi^+\pi^-p) \leq 0.85 \pm 0.35$   $\mu\text{b}$  for  $E_\gamma = 4.3$  GeV [54],  $\sigma(\gamma p \rightarrow \rho_3^0 p \rightarrow \pi^+\pi^-p) < 0.1$   $\mu\text{b}$  and  $\sigma(\gamma p \rightarrow \rho_3^0 p \rightarrow \pi^+\pi^-\pi^+\pi^-p) < 1$   $\mu\text{b}$  for  $E_\gamma = 5.25$  GeV [53]. The results of Refs. [53,54] have been based on very poor statistics and at present it is not clear whether they have much to do with the  $\rho_3^0(1690)$ . In this situation, a reliable estimate of the cross section for the charge exchange reaction  $\gamma p \rightarrow \rho_3^+ n \rightarrow \pi^+\pi^0\pi^+\pi^-n$  is rather difficult to obtain. If there occurs an universal relation between the Pomeron contribution and the  $f_2$  Regge pole contribution in the reactions  $\gamma p \rightarrow \rho^0 p$  and  $\gamma p \rightarrow \rho_3^0 p$  and if exchange degeneracy [46] and the naive quark counting rules hold for the  $\rho$ ,  $a_2$ , and  $f_2$  exchanges in  $\gamma N \rightarrow \rho_3 N$ , then it is hoped that  $\sigma(\gamma p \rightarrow \rho_3^+ n)$  would be an odder of magnitude smaller than  $\sigma(\gamma p \rightarrow \rho'^+ n)$ .

Judging by the data presented in Table 2,  $\sigma(\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N) \approx 7$   $\mu\text{b}$  at  $E_\gamma \approx 6$  GeV. We have shown that a part of the cross section of about 3  $\mu\text{b}$  can be explained by a few processes with the appreciable cross sections due to rather simple mechanisms (see Eqs. (15) – (18)). The remainder of the total cross section is probably distributed among a great many of more “fine” channels a set of which has been indicated by us only partly. In this sense, the presented analysis is preliminary and further theoretical investigations are needed. Undoubtedly, a further crucial progress in refinement of the cross sections for various photoproduction channels will be connected with the accurate measurements at JLAB. It is for experimentalists to decide.

Let us now consider very briefly the reaction  $\gamma p \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++}$ . The available data for  $E_\gamma < 10$  GeV are presented in Table III. According this information, the most probable value of  $\sigma(\gamma p \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++})$  for  $4 \leq E_\gamma \leq 6$  GeV is about  $1.87 \pm 0.38$   $\mu\text{b}$ . As is seen from Table III, the only observable partial channel  $\gamma p \rightarrow \omega\pi^-\Delta^{++}$  [53,54] can contribute to the  $\pi^-\pi^0\pi^+\pi^-\Delta^{++}$  production cross section up to 1  $\mu\text{b}$ . As for the estimate of the cross section for the channel  $\gamma p \rightarrow \rho'^-\Delta^{++} \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++}$ , it can be obtained by multiplying the cross section value in Eq. (18) by the coefficient 1.75. Similarly we already have done by passing from Eq. (12) to Eq. (14) in the case of  $X^-$  production. We thus expect  $\sigma(\gamma p \rightarrow \rho'^-\Delta^{++} \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++}) \approx (0.1 - 0.15)$   $\mu\text{b}$ . In principle, the

reaction involving  $\Delta^{++}$  production may be found to be rather favorable (in the sense of the background conditions) to the search for the  $X^-$  signal.

In conclusion we note that the reaction  $\gamma p \rightarrow \omega\pi^-\pi^+p$  may be dominated by associated  $\omega\pi^-\Delta^{++}$  production (see Table III). This point has been especially emphasized, for example, in Ref. [54]. The cross section for  $\gamma p \rightarrow \omega\pi^-\pi^+p$  with the  $\omega\pi^-\Delta^{++}$  channel excluded is not likely to be over  $(0.5 - 1)$   $\mu\text{b}$  at  $E_\gamma \approx 6$  GeV (see Table III). In our opinion, peripheral production of the  $\omega\pi^-\pi^+$  systems is of special interest in the reaction  $\gamma p \rightarrow \omega\pi^-\pi^+p$ . In particular, the  $\omega(1600)$  and  $\omega_3(1670)$  resonances have to be photoproduced diffractively in the  $C$ -odd  $\omega\pi^-\pi^+$  states with the cross sections an order of magnitude smaller than are now available (or expected) for  $\gamma p \rightarrow \rho'^0 p$  and  $\gamma p \rightarrow \rho_3^0 p$  respectively (i.e., for example,  $\sigma(\gamma p \rightarrow \omega(1600)p \rightarrow \omega\pi^-\pi^+p) \approx 0.1 \mu\text{b}$ ). To search for the  $C$ -even resonances, the  $\omega\rho^0$  mode is most suitable. In fact, of the known (“tabular”)  $q\bar{q}$  resonances in this decay mode there are only the  $a_2(1320)$  [26,78] and, possibly,  $\pi_2(1670)$  and  $\pi(1800)$  states [78]. Therefore, the appreciable enhancement with  $(J^P, |J_z|) = (2^+, 2)$  found by the ARGUS group in the cross section of the reaction  $\gamma\gamma \rightarrow \omega\rho^0$  for  $1.5 \leq W_{\gamma\gamma} \leq 2.1$  GeV [79] may be interpreted as evidence for a  $q^2\bar{q}^2$  MIT-bag state which is strongly coupled to the  $\omega\rho^0$  channel [20,17]. In the notations of Ref. [20], it is the  $C_\pi^0(36)$  state with  $I^G(J^{PC}) = 1^-(2^{++})$  being the partner of the  $X(1600, 2^+(2^{++}))$ . Note, without going into detailed estimates, that we would expect the cross section for  $\gamma p \rightarrow C_\pi^0(36)p \rightarrow \omega\rho^0p$  at a level of about  $0.075 \mu\text{b}$  at  $E_\gamma \approx 6$  GeV. This value should be compared with the estimate given by Eq. (12). The expected enhancement of the  $C_\pi^0(36)$  photoproduction cross section by comparison with the case of  $X^\pm$  is due to several factors. For example, one of them is a strong coupling of the  $\omega$  exchange (which we consider as a major mechanism of the reaction  $\gamma p \rightarrow C_\pi^0(36)p$ ) to the nucleons. Also, we would expect  $\sigma(\gamma p \rightarrow C_\pi^+(36)n \rightarrow \omega\rho^+n) \approx (5/81)\sigma(\gamma p \rightarrow C_\pi^0(36)p \rightarrow \omega\rho^0p) \approx 0.0046 \mu\text{b}$  and, for  $C_\pi^s(36)$  and  $C^s(36)$  MIT-bag state production,  $\sigma(\gamma p \rightarrow C_\pi^{s+}(36)n \rightarrow \phi\rho^+n) \approx 2\sigma(\gamma p \rightarrow C_\pi^{s0}(36)p \rightarrow \phi\rho^0p) \approx (10/81)\sigma(\gamma p \rightarrow C_\pi^0(36)p \rightarrow \omega\rho^0p)B(C_\pi^s(36) \rightarrow \phi\rho) \approx (0.0092 \mu\text{b})B(C_\pi^s(36) \rightarrow \phi\rho)$  and  $\sigma(\gamma p \rightarrow C^s(36)p \rightarrow \phi\omega p) \approx (2/9)\sigma(\gamma p \rightarrow C_\pi^0(36)p \rightarrow \omega\rho^0p)B(C^s(36) \rightarrow \phi\omega) \approx (0.0166 \mu\text{b})B(C^s(36) \rightarrow \phi\omega)$ . A search for the threshold enhancements in the  $K^*\bar{K}^*$  and  $\omega\omega$  final states in photoproduction would also be an important complement to the  $\gamma\gamma$  experiments and to other approaches. Note that it is not yet clearly established that some threshold enhancements in  $\gamma\gamma \rightarrow VV'$  are due to exotic meson resonances.

## References

- [1] A.R. Dzierba, in *Proceedings of the Second Workshop on Physics and Detectors for DAΦNE'95*, Frascati, 1995, edited by R. Baldini, F. Bossi, G. Capon, and G. Pancheri, Frascati Physics Series, Vol. 4 (INFN, Frascati, 1996), p. 99.
- [2] A.R. Dzierba, in *Proceedings of the First Workshop on Hadron Dynamics with the New DAΦNE and CEBAF Facilities*, Frascati, 1996, edited by R. Baldini, E. De Sanctis, G. Pancheri, and G. Ricco, Nucl. Phys. **A623**, 142c (1997); G.S. Adams, ibid. **A623**, 158c (1997).
- [3] P.R. Page, Phys. Lett. **B415**, 205 (1997); A. Afanasev and P.R. Page, Phys. Rev. D **57**, 6771 (1998).

- [4] J. Napolitano, in *Proceedings from Jefferson Lab/NCSU Workshop on Hybrids and Photoproduction Physics* (JLAB, 1997), p. 1; T. Barnes, *ibid.* p. 37; G. Blackett *et al.*, *ibid.* p. 287; R.T. Jones, *ibid.* p.369; V.D. Burkert and R. Ent, *ibid.* p.385; P. Page, *ibid.* p.589.
- [5] M.N. Achasov *et al.*, presented by S.I. Serednyakov, in *Proceedings of the Seventh International Conference on Hadron Spectroscopy*, HADRON'97, BNL, Upton, NY, 1997, edited by S.-U. Chung and H.J. Willutzki, AIP Conference Proceedings 432 (Woodbury, NY, 1998), p. 26; M.N. Achasov *et al.*, presented by V.N. Ivanchenko, *ibid.* p. 783.
- [6] M.N. Achasov *et al.*, Preprint Budker INP 97-78, Novosibirsk, 1997, hep-ex/9710017; Preprint Budker INP 98-65, Novosibirsk, 1998, hep-ex/9809013.
- [7] M.N. Achasov *et al.*, Phys. Lett. **B438**, 441 (1998); **B440**, 442 (1998).
- [8] N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. **B315**, 465 (1989).
- [9] S. Fajfer and R.J. Oakes, Phys. Rev. D **42**, 2392 (1990); F.E. Close, N. Isgur, and S. Kumano, Nucl. Phys. **B389**, 513 (1993); J.L. Lucio and M. Napsuciale, Phys. Lett. **B331**, 418 (1994).
- [10] N.N. Achasov, V.V. Gubin, and E.P. Solodov, Phys. Rev. D **55**, 2672 (1997); N.N. Achasov, V.V. Gubin, and V.I. Shevchenko, *ibid.* **56**, 203 (1997); N.N. Achasov and V.V. Gubin, *ibid.* **56**, 4084 (1997); **57** 1987 (1998).
- [11] Particle Data Group, R.M. Barnett *et al.*, Phys. Rev. D **54**, 46 (1996); **54**, 369 (1996); **54**, 557 (1996).
- [12] R. Brandelik *et al.*, Phys. Lett. **97B**, 448 (1980); D.L. Burke *et al.*, *ibid.* **103B**, 153 (1981); M. Althoff *et al.*, Z. Phys. C **16**, 13 (1982); H.-J. Behrend *et al.*, *ibid.* **21**, 205 (1984); Ch. Berger *et al.*, *ibid.* **38**, 521 (1988); H. Aihara *et al.*, Phys. Rev. D **37**, 28 (1988).
- [13] H. Albrecht *et al.*, Z. Phys. C **50**, 1 (1991).
- [14] H. Kolanoski, in *Proceedings of the 5th International Workshop on Photon-Photon Collisions*, Aachen, 1983, edited by Ch. Berger, Lecture Notes in Physics, Vol. 191 (Springer, New York, 1983), p. 175; H. Albrecht *et al.*, Phys. Lett. **B217**, 205 (1989); H.-J. Behrend *et al.*, *ibid.* **B218**, 493 (1989).
- [15] H. Albrecht *et al.*, Phys. Lett. **B267**, 535 (1991).
- [16] M. Poppe, Intern. J. Mod. Phys. A **1**, 545 (1986); Ch. Berger and W. Wagner, Phys. Rep. **146**, 1 (1987); J. Olsson, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies*, Hamburg, 1987, edited by W. Bartel and R. Rückl (North Holland, 1987), p. 613; A. Buijs, *Production of Four-Prong Final States in Photon-Photon Collisions*, Ph.D. Thesis, Utrecht, 1987; H. Kolanoski and P. Zerwas, in *High Energy Electron-Positron Physics*, edited by A. Ali and P. Söding (World Scientific, Singapore, 1988); H. Albrecht *et al.*, Phys. Rep. **276**, 223 (1996); S. Godfrey and J. Napolitano, *Light Meson Spectroscopy*, submitted to Rev. Mod. Phys.; hep-ph/9811410, 1998.

- [17] N.N. Achasov and G.N. Shestakov, Usp. Fiz. Nauk **161**, No.6, 53 (1991) [Sov. Phys. Usp. **34**, No.6, 471 (1991)]; Phys. Rev. D **52**, 6291 (1995).
- [18] N.N. Achasov, S.A. Devyanin, and G.N. Shestakov, Phys. Lett. **108B**, 134 (1982); Z. Phys. C **16**, 55 (1982).
- [19] B.A. Li and K.F. Liu, Phys. Lett. **118B**, 435 (1982); **124B**, 550(E) (1983); Phys. Rev. Lett. **51**, 1510 (1983).
- [20] R.L. Jaffe, Phys. Rev. D **15**, 267 (1977); **15**, 281 (1977).
- [21] G. Alexander, U. Maor, and P.G. Williams, Phys. Rev. D **26**, 1198 (1982); G. Alexander, A. Levy, and U. Maor, Z. Phys. C **30**, 65 (1986); G. Alexander and U. Maor, Phys. Rev. D **46**, 2882 (1992); B. Bajc, S. Prelovšek, and M. Rosina, Z. Phys. A **356**, 187 (1996).
- [22] N.N. Achasov and G.N. Shestakov, Phys. Lett. **B203**, 309 (1988); H. Kolanoski, Z. Phys. C **39**, 543 (1988).
- [23] S.-U. Chung, in *Proceedings of the 6th International Conference on Hadron Spectroscopy*, HADRON'95, Manchester, UK, 1995, edited by M.C. Birse, G.D. Lafferty, and J.A. McGovern (World Scientific, Singapore, 1996), p. 19.
- [24] N.N. Achasov and G.N. Shestakov, Intern. J. Mod. Phys. A **7**, 4313 (1992).
- [25] H. Burkhardt and A.J.G. Hey, Nucl. Phys. **B108**, 514 (1976); R. Kokoski and N. Isgur, Phys. Rev. D **35**, 907 (1987).
- [26] Particle Data Group, C. Caso *et al.*, Euro. Phys. J. C **3**, 1 (1998).
- [27] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **56**, 212 (1997).
- [28] M. Atkinson *et al.*, Z. Phys. C **30**, 531 (1986).
- [29] Particle Data Group, C.G. Wohl *et al.*, Rev. Mod. Phys. **56**, S19 (1984); **56**, S167 (1984).
- [30] A.B. Clegg and A. Donnachie, Z. Phys. C **62**, 455 (1994); A. Donnachie, Nucl. Phys. **A623**, 135c (1997).
- [31] H. Bingham *et al.*, Phys. Lett. **41B**, 653 (1972).
- [32] M. Davier *et al.*, Nucl. Phys. **B58**, 31 (1973).
- [33] P. Schacht *et al.*, Nucl. Phys. **B81**, 205 (1974).
- [34] D.P. Barber *et al.*, Z. Phys. C **4**, 169 (1980).
- [35] D. Aston *et al.*, Nucl. Phys. **B189**, 15 (1981).
- [36] M. Atkinson *et al.*, Z. Phys. C **26**, 499 (1985).
- [37] L. Stodolsky and J.J. Sakurai, Phys. Rev. Lett. **11**, 90 (1963); L. Stodolsky, Phys. Rev. **134**, B1099 (1964).

- [38] H.-J. Behrend *et al.*, Z. Phys. C **56**, 382 (1992) and Refs. herein.
- [39] M. Acciarri *et al.*, Phys. Lett. **B413**, 147 (1997); H. Albrecht *et al.*, Z. Phys. C **74**, 469 (1997).
- [40] D. Antreasyan *et al.*, Phys. Rev. D **33**, 1847 (1986); T. Oest *et al.*, Z. Phys. C **47**, 343 (1990).
- [41] P. Singer, Phys. Rev. D **27**, 2223 (1983).
- [42] N.N. Achasov, S.A. Devyanin, and G.N. Shestakov, Z. Phys. C **27**, 99 (1985).
- [43] M. Jacob and G.C. Wick, Ann. Phys. (N.Y.) **7**, 404 (1954); M. Gell-Mann *et al.*, Phys. Rev. **133**, B145 (1964); G.C. Fox and E. Leader, Phys. Rev. Lett. **18**, 628 (1964).
- [44] F.A. Berends, A. Donnachie, and D.L. Weaver, Nucl. Phys. **B4**, 103 (1967).
- [45] G.L. Kane *et al.*, Phys. Rev. Lett. **25**, 1519 (1970).
- [46] R. Worden, Nucl. Phys. **B37**, 253 (1972).
- [47] M. Guidal, J.-M. Laget, and M. Vanderhaeghen, Nucl. Phys. **A627**, 645 (1997) and Refs. herein.
- [48] A.V. Barnes *et al.*, Phys. Rev. Lett. **37**, 76 (1976).
- [49] K. Lübelsmeyer, in *Proceedings of the 4th International Symposium on Electron and Photon Interactions at High Energies*, Liverpool, 1969, edited by D.W. Braben and R. E. Rand (Daresbury Nucl. Phys. Lab., 1969), p. 45; in *Proceedings of the XVth International Conference on High Energy Physics*, Kiev, 1970, edited by V. Shelest, Yu. Budagov, L. Jenkovsky, A. Komar, and V. Kukhtin (Naukova Dumka, Kiev, 1972), p. 296.
- [50] R. Anderson *et al.*, Phys. Rev. D **1**, 27 (1970); M. Braunschweig *et al.*, Nucl. Phys. **B20**, 191 (1970).
- [51] D.W.G.S. Leith, in *Proceedings of the Eleventh Session of the Scottish Universities Summer School in Physics on Hadronic Interactions of Electrons and Photons*, Midlothian, 1970, edited by J. Cumming and H. Osborn (Academic Press, London, 1971), p. 195.
- [52] R. Erbe *et al.*, Phys. Rev. **175**, 1669 (1968).
- [53] J. Ballam *et al.*, Phys. Lett. **B30**, 421 (1969). In addition, see the relevant data on the reaction  $\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$  at higher energies presented in M. Atkinson *et al.*, Phys. Lett. **127B**, 132 (1983); Nucl. Phys. **B231**, 15 (1984).
- [54] Y. Eisenberg *et al.*, Phys. Rev. Lett. **22**, 669 (1969).

- [55] G. Gidal *et al.*, Phys. Rev. Lett. **23**, 994 (1969); D.R.O. Morrison, *Review of Quasi Two-Body Reactions*, Rapporteur's Talk given at the XVth International Conference on High Energy Physics, Kiev, 1970; It has been appeared as Preprint CERN/D.Ph.11/PHYS.71-10 and Preprint ITP-71-66E, Kiev, 1971.
- [56] V. Flaminio *et al.*, *Compilation of Cross-Sections I:  $\pi^+$  and  $\pi^-$  induced Reactions*, CERN-HERA 83-01, Geneva, 1983.
- [57] J. Abramson *et al.*, Phys. Rev. Lett. **36**, 1432 (1976) and Refs. herein.
- [58] H.G. Hilpert *et al.*, Nucl. Phys. **B21**, 93 (1970); P. Benz *et al.*, Nucl. Phys. **B79**, 10 (1976); D.P. Barber *et al.*, Z. Phys. C **2**, 1 (1979).
- [59] R. Erbe *et al.*, Phys. Rev. **188**, 2060 (1969).
- [60] M. Davier *et al.*, Phys. Rev. D **1**, 790 (1970).
- [61] G. Alexander *et al.*, Phys. Rev. Lett. **26**, 340 (1971).
- [62] Y. Eisenberg *et al.*, Nucl. Phys. **B25**, 499 (1971).
- [63] R. Schiffer *et al.*, Nucl. Phys. **B38**, 628 (1972).
- [64] Y. Eisenberg *et al.*, Phys. Rev. D **5**, 15 (1972).
- [65] J. Ballam *et al.*, Phys. Rev. D **5**, 545 (1972).
- [66] H.H. Bingham *et al.*, Phys. Rev. D **8**, 1277 (1973).
- [67] G. Alexander *et al.*, Phys. Rev. D **8**, 1965 (1973).
- [68] G. Alexander *et al.*, Nucl. Phys. **B68**, 1 (1974).
- [69] W. Struczinski *et al.*, Nucl. Phys. **B108**, 45 (1976).
- [70] P. Benz *et al.*, Nucl. Phys. **B115**, 385 (1976).
- [71] D.P. Barber *et al.*, Z. Phys. C **26**, 343 (1984).
- [72] C.A. Nelson *et al.*, Phys. Rev. D **17**, 647 (1978).
- [73] J. Ballam *et al.*, Phys. Rev. D **7**, 3150 (1973).
- [74] T.H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978).
- [75] G. Alexander *et al.*, Phys. Lett. **57B**, 487 (1975).
- [76] G. Ascoli *et al.*, Phys. Rev. Lett. **16**, 1712 (1968).
- [77] R.L. Thews, Phys. Rev. **175**, 1749 (1968); K. Schilling, P. Seyboth, and G. Wolf, Nucl. Phys. **B15**, 397 (1970); **B18**, 332(E) (1970).

- [78] A. Popov and D. Ryabchikov, in *Proceedings of the Seventh International Conference on Hadron Spectroscopy*, HADRON'97, BNL, Upton, NY, 1997, edited by S.-U. Chung and H.J. Willutzki, AIP Conference Proceedings 432 (Woodbury, NY, 1998), p. 373.
- [79] E. Križnič, *Production of  $\omega\rho^0$ ,  $\rho^0\phi$  and  $\omega\phi$  in Two-Photon Interactions at the ARGUS Spectrometer*, Ph.D. Thesis, Univerza v Ljubljani, 1993, IJS DP - 6928, Ljubljana, Slovenija, 1994.

Table I. Classification of the  $\rho^\pm\rho^0$  states.

$I^G(J^{PC})$ series, $k = 0, 1, 2, \dots$	Possible resonance states	$^{2S+1}L_J$ configurations for lower $J$ states
$1^+((2k+1)^{--})$	$\rho(1700)$ , $\rho_3(1690)$	$(^1P_1, ^5P_1, ^5F_1); (^5P_3, ^1F_3, ^5F_3, ^5H_3)$
$1^+((2k+1)^{+-})$	$b_1(1235)$	$^3S_1, ^3D_1$
$1^+((2k+2)^{--})$	$\rho_2(?)$	$^5P_2, ^5F_2$
$1^+((2k+2)^{+-})$	are absent in $q\bar{q}$ system	$^3D_2$
$2^+((2k+1)^{-+})$	$q^2\bar{q}^2$	$^3P_1, ^3F_1$
$2^+((2k+1)^{++})$	$q^2\bar{q}^2$	$^5D_1$
$2^+((2k)^{-+})$	$q^2\bar{q}^2$	$(^3P_0); (^3P_2)$
$2^+((2k)^{++})$	$q^2\bar{q}^2, X(1600, 2^+(2^{++}))$	$(^1S_0, ^5D_0); (^5S_2, ^1D_2, ^5D_2, ^5G_2)$

Table II. Total and partial cross sections of the reactions  $\gamma N \rightarrow \pi^\pm\pi^0\pi^+\pi^-N$ .

$E_\gamma$ (GeV)	Reaction (Ref. [62])	Cross section ( $\mu\text{b}$ )	$E_\gamma$ (GeV)	Reaction (Refs. [61,63,68,70-72])	Cross section ( $\mu\text{b}$ )
4.3	$\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$	$7.5 \pm 1.0$	$6.9 - 8.1$	$\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$	$4.85 \pm 0.89$
	$\gamma n \rightarrow \omega\pi^-p$	$1.4 \pm 0.5$	$3.6 - 5.1$	$\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$	$11.0 \pm 2.2$
	$\gamma n \rightarrow \rho^-\pi^+\pi^-p$	$1.1 \pm 0.5$	7.5	$\gamma n \rightarrow \pi^-\pi^0\pi^+\pi^-p$	$6.1 \pm 0.8$
	$\gamma n \rightarrow \rho^0\pi^0\pi^-p$	$1.8 \pm 1.0$	$2.5 - 5.3$	$\gamma n \rightarrow \omega\pi^-p$	$1.6 \pm 0.5$
	$\gamma n \rightarrow \rho^+\pi^-\pi^-p$	$0.5 \pm 0.5$	$4.2 - 4.8$	$\gamma p \rightarrow \omega\Delta^+ \rightarrow \omega\pi^+n$	$0.83 \pm 0.10$
	$\gamma n \rightarrow \pi^+\pi^-\pi^0\Delta^0$	$0.6 \pm 0.6$	8.9	$\gamma N \rightarrow \omega\Delta \rightarrow \omega\pi^\pm N$	$0.24 \pm 0.023$

Table III. Cross sections for the reactions  $\gamma p \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++}$  and  $\gamma p \rightarrow \omega\pi^-\pi^+p$ , and for their common partial channel  $\gamma p \rightarrow \omega\pi^-\Delta^{++}$ .

$E_\gamma$ (GeV)	$\sigma(\gamma p \rightarrow \pi^-\pi^0\pi^+\pi^-\Delta^{++})$ ( $\mu\text{b}$ )	$\sigma(\gamma p \rightarrow \omega\pi^-\Delta^{++})$ ( $\mu\text{b}$ )	$\sigma(\gamma p \rightarrow \omega\pi^-\pi^+p)$ ( $\mu\text{b}$ )	Refs.
4.3	$2.4 \pm 0.8$	$\approx 1$	$1.42 \pm 0.45$	[54]
4 – 6	$1.3 \pm 0.3 \pm 0.2$	—	$1.6 \pm 0.2 \pm 0.24$	[69]
4.5 – 5.8	$\leq 2.4 \pm 1.1$	—	$2.4 \pm 0.9$	[59]
5.25	$3.9 \pm 1.5$	$0.5 \pm 0.2$	$1.5 \pm 0.4$	[53]

## Figure caption

**Fig. 1.** The ARGUS results on the ( $J^P, J_z$ ) = (2 $^+$ ,  $\pm 2$ ) partial cross sections for the reactions  $\gamma\gamma \rightarrow \rho^0\rho^0$  [13] (open circles) and  $\gamma\gamma \rightarrow \rho^+\rho^-$  [15] (full squares).  $W_{\gamma\gamma}$  is the invariant mass of the  $\gamma\gamma$  system. For an ordinary isospin 0 resonance one expects  $\sigma(\gamma\gamma \rightarrow \rho^+\rho^-)/\sigma(\gamma\gamma \rightarrow \rho^0\rho^0) = 2$  (and 1/2 for a pure isospin 2 resonance). Instead, the observed ratio is lower than 1/2. A resonance interpretation for such a result in terms of  $q^2\bar{q}^2$  states thus requires the presence of a flavor exotic  $I = 2$  resonance which interferes with isoscalar contributions [11,17,18].

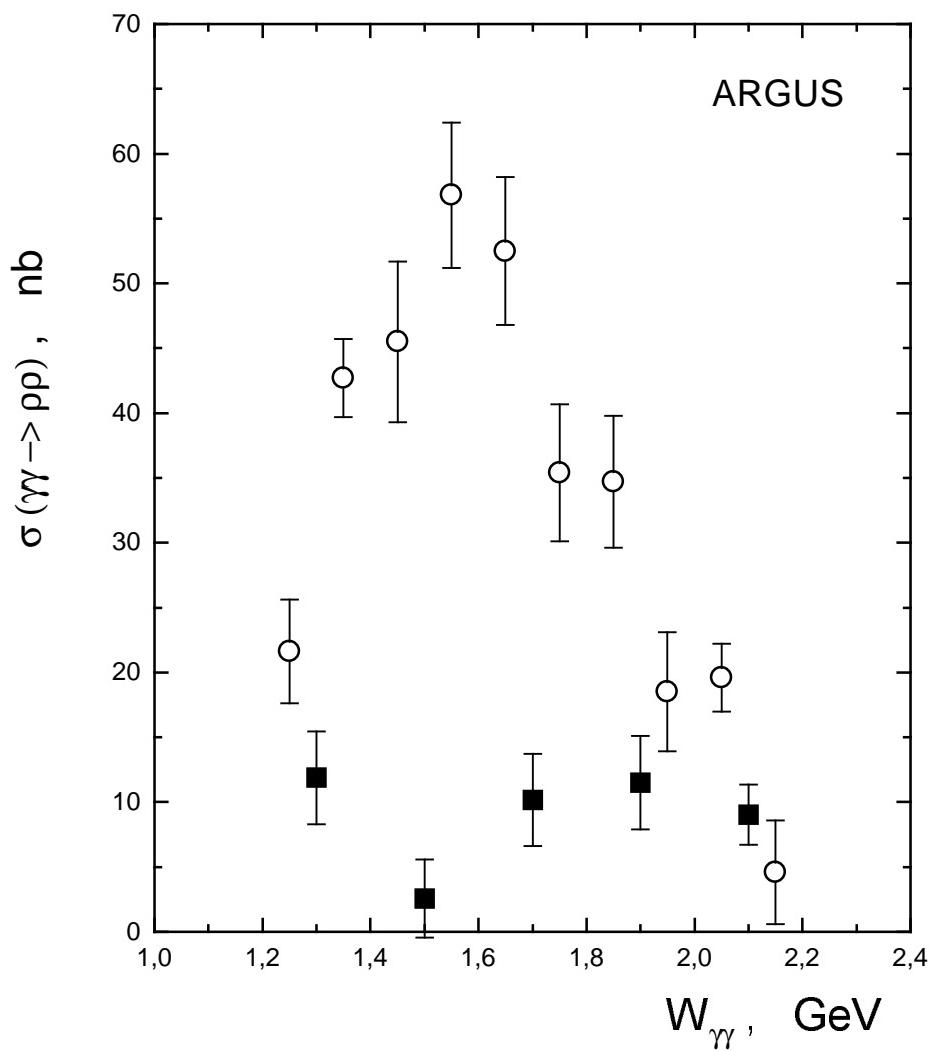


Fig. 1.